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Design metrics to normalize and compare LCA results in household appliance sector: outcomes from literature analysis

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Abstract

Nowadays, household appliance manufacturers shall adapt their engineering methods and tools to meet environmental concerns. Despite the environmental assessment of products and services is usually carried out based on Life Cycle Assessment (LCA) standardized approach (e.g., ISO14040/14044), numerous assumptions are up to practitioners' discretion, such as functional unit, system boundaries, or allocation method. These choices may lead to a results discrepancy between equivalent studies, even if similar products are considered. The goal of this work is to present a method for determining appropriate metrics (indices) that enable designers to compare the findings of LCA analysis carried out in the context of home appliances. The indices refer to the cooker hoods family and they were developed through a systematic literature review. LCA studies carried out from 2006 to 2022 were the basis for the identification of design features and parameters that allow the normalization of results retrieved in different studies. These features served as the basis for the indices formulation, enabling an accurate comparison of appliances from the same family. The application of these indices, according to the results, makes LCA evaluations of cooker hood models with different performances and design factors comparable. Finally, the same approach can be adopted to create a framework and a useful guide to conduct future LCA studies for other household appliance families with the aim to provide a normalization basis to compare product design alternatives.

Keywords: Household appliances, LCA, design index, normalization, cooker hoods

1. Introduction

The daily use of household appliances generates significant environmental concerns such as electric energy consumption, greenhouse gas emissions, and air pollution [1]. This is the reason why, Life Cycle Assessment (LCA) has been adopted by manufacturers, practitioners, and academics to explore environmental risks associated with household appliances manufacturing, use, and disposal. In the last two decades, due to the increased effort of the international community against environmental pollution and the establishment of the LCA methodology as a recognized standard, several works have been developed with the goal of understanding, characterizing, and implementing corrective eco-design actions in the field of household appliances [2][3]. LCA-based studies have been conducted for a variety of products, including cooking appliances [4][5], food storage systems [6][7], and washing machines [8], among others. LCA has grown in maturity and methodological robustness over time, resulting in international standardization of the overall procedure [9][10]. However, the overarching framework for conducting an LCA study offers practitioners a wide range of options for carrying out the analysis. This lack of constraints in developing the LCA studies for the system of interest led to heterogeneous assumptions and results among the research available [11]. The discrepancy stems mostly from the functional unit's definition, the assumptions about the product's lifespan, the differences in system boundaries involved, the selection of the environmental

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categories, and the reporting of the outcomes [12]. Inconsistencies persist even for assessments on the same product, making it difficult to compare findings and identify patterns that are useful for engineers and designers operating in the household appliances context. Comparison of LCA outcomes conducted by various practitioners on comparable products became mistaken when focusing solely on the functional unit. Hence, this paper presents a method to select several design parameters that can be used to define a normalization basis, allowing for a fair comparison of LCA studies in the field of household appliances. Hopefully, the wide acceptance of this method will ease the alignment of previous and future studies in this specific field. Individual aspects of LCA works developed for specific household appliance families have been defined by using a systematic literature review with the goal of addressing the primary lacks in this field (i.e., a normalized presentation of the outcomes). In particular, the work reports metrics (indices) developed for the cooker hoods' family, based on their design parameters and features. The goal is to create a framework and a useful guide to conduct future LCA in the field of home appliances, providing a tool for comparing different analyses performed by different practitioners, and creating a normalization basis used to compare product design alternatives. The novelty of the presented work is a definition of a set of indices necessary to compare the results of different studies and to identify design solutions that can be adopted for the implementation of eco-design actions in this field.

2. Systematic literature review

This work is based on a systematic literature review of LCA studies for household appliances. The large number of works developed in this field were considered as a need to establish robust impact comparison indices, retrieving appropriate design parameters to make LCA results comparable.

2.1. Data source and scope definition

Firstly, household appliance families were clearly defined before starting the review. Based on the definition of "large household appliances" identified in the European directive on waste electrical and electronic equipment (WEEE) [13], also known as "white goods" in grey literature, nine families have been identified for this study: (i) cold food storage systems (e.g., fridge); (ii) food freezing systems; (iii) heat cooking systems (e.g., oven, hob); (iv) kitchen vacuum systems (e.g., cooker hood); (v) dishes washing; (vi) house heating systems (e.g., electric radiator, oil/gas boiler, heat pump); (vii) house cooling systems; (viii) clothes washing systems; (ix) clothes drying systems. All electronic devices that are not related to household chores (e.g., televisions, smartphones, computers) or leisure devices were not considered within the scope of the study, as well as professional or public systems or devices. The review was done on three databases *Scopus*, *Springer,* and *Taylor&Francis* which are considered the most relevant in engineering and life science fields. The review was limited to English original articles, conferences papers, and book chapters. The fields covered by the review were: engineering, environmental sciences, energy, and material sciences. This choice allows avoiding a high number of out-scope papers in the research results. The studies covered a period starting from the year of the last revision for the ISO 14040/4 standards [9][10] (2006) till the date of the review (2022). Given the rapid evolution of the LCA discipline, this decision was made to prevent using outdated research that could lead to misleading conclusions. Moreover, the ISO standard was considered the reference regarding LCA methodology, and the indices were developed in compliance with these standards.

2.2. Search strategy

Keyword-based search procedure for each product family is presented here. A dedicated search procedure for "general household appliances" was done to include possible other works. Keywords and Boolean operators (and/or) used for the searching process are presented in Fig. 1.

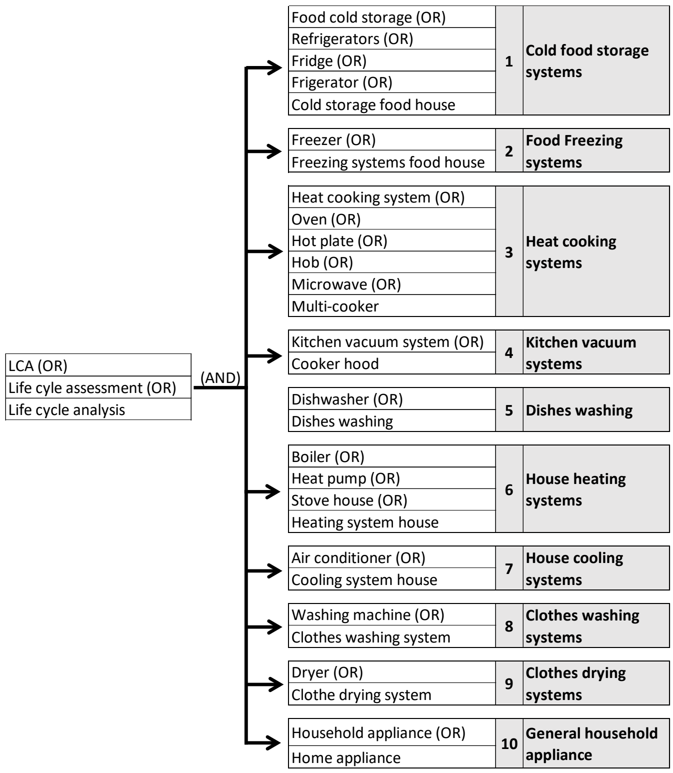

Fig. 1. Keywords with Boolean search strategy.

The search strategy was performed using a filter based on title, abstract, and keywords, and 595 records were found using this searching approach.

2.3. Studies selection and quality assessment

After this first search, a screening process was carried out to eliminate duplicates and to avoid studies out of the scope of this review. The number of records was decreased by the screening procedure, and only 10% of the records from the first search were chosen as final candidates (Fig. 2). The screening process was made by reading the abstract of the papers, even though some papers were fully inspected, depending on the accuracy of their description. The following criteria were used to exclude not relevant records:

- the study does not provide an LCA analysis in compliance with the ISO 14040/44 standards [9][10];
- the study does not concern large household appliances but is focused on leisure electronic devices;
- the analysis does not deal with the framework of private housing (e.g., industry, catering, sharing systems);
- the study is only focused on a part of the device and not the entire device itself (e.g., packaging, electronic part);
- the study aims to compare only the use phase, excluding the manufacturing one (e.g., heating with gas, wood, or electricity);
- the study only focuses on life cycle costing (LCC) or social life cycle assessment (S-LCA);
- the study only focuses on building design and impacts on appliance consumption.

Fig. 2 provides a broad overview of the articles selection procedure, generating the final portfolio of 60 publications. The list of references is provided as additional materials.

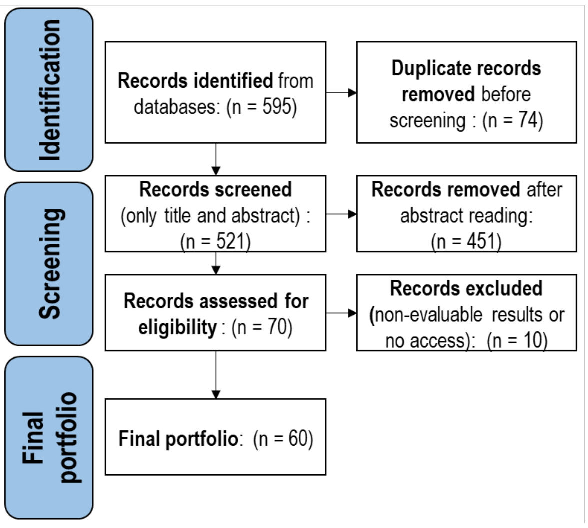

Fig. 2. Records selection process

To accomplish with the purpose of the study, technical reports [14][15] and standards [16][17] related to the household appliances and energy consumption in household appliances were included as supplementary material for this review.

3. Metrics definition for LCA comparison

This section presents the outcome of the systematic literature review, including the criteria adopted to develop the indices, the limitations of the method and the final equations.

3.1. Indices creation method

To accurately develop environmental comparability indices, each record from the collection were carefully examined. Data were collected within a structured framework (Excel file) including: (i) LCA information (e.g., goal and scope, reference flow, functional unit, system boundaries, attributional method, database used), (ii) product design parameters (e.g., efficiency, max power, daily/year consumption, lifetime), and (iii) results from the LCA analysis (e.g., indicator results). The framework was developed to collect data even if the studies were conducted with different Life Cycle Impact Assessment (LCIA) methods, such as CML-IA, Eco-Indicator 99, or ReCiPe method including a dedicated section for each indicator [18]. The motivation for the use of a systematic literature review, rather than relying exclusively on the ISO 14040/44 standards, deals with the possibility to retrieve and use specific design data that allow for a fair comparison among the different types of appliances. These data allowed the establishment of proper indices useful for comparative LCA analyses. Due to page restriction, only the indices referring to the kitchen vacuum systems (i.e., cooker hoods) are presented in this paper, while the indices referred to the other household appliance families will be provided in future works. Focusing on the kitchen vacuum systems, design features such as the total cooking surface area to cover (A), the maximum air flow rate (Q), and the maximum power (P) were used to define the normalization indices for the different life cycle phases. Then, even if different functional units were defined in the analyzed works, the indices allow making a fair comparison among the products, considering their design features.

3.2. Choice of the boundaries and limits of the indices

Three indices were defined based on the three main phases that characterize these products: (i) materials and manufacturing, (ii) use, and (iii) end-of-life (EoL). The transportation phase was not considered, since it is negligible compared to the other phases as reported in many studies for this kind of product [19][20]. The material selection and manufacturing processes were considered in a single phase since the two choices are strictly related and performed at the same time during the design process. In general, the comparison of the LCIA outcomes from different studies is meaningful only when the same LCIA methodology is used. However, in some cases, the comparison is still allowed even if a different LCIA method is adopted. It is the case of Global Warming Potential (GWP) obtained by the CML-IA method and Climate Change (CC) obtained by ReCiPe method, since both indicators are based on the same approach (IPCC methodology). On the other hand, when other midpoints or endpoints are considered, possible inaccuracies can occur, making indices analysis more difficult to interpret. Another limitation of the normalization procedure is related to the time frame considered in the selection of the LCIA method (generally 100 years, corresponding to 100% of the final records), as well as the selection of the allocation method. Moreover, knowing that home appliances are energy-consuming products, the same grid mix shall be considered for a fair comparison of the results referring to the operational phase. This is an additional limit of the proposed approach.

3.3. Presentation of the indices

The normalization indices were defined for the different families of home appliances. For the sake of clarity, only the indices referring to the kitchen vacuum systems are reported.

The choice of this household appliances family as a representative case study for this work was made for the following reasons: (i) the works retrieved for this family used the same grid mix (Italian grid mix) which allows a fair comparison of the outcomes, (ii) there are at least two works that present all the necessary data for the indices assessment, and (iii) assumptions and design features characterizing the products present relevant differences. Although the works concerning this household appliance family were developed using different LCIA methods, which could limit the indices' usability, it was possible to compare endpoint results, considering weaknesses and possible shortcomings. The indices definition was carried out through the analysis of the retrieved works focusing on the definition of functional units adopted for the LCA analysis. Equation 1 refers to the Manufacturing Index (*Mi*), while Equation 2 and Equation 3 refer to the Use phase Index (*Ui*), and the EoL Index (*Ei*), respectively.

$$Mi = \frac{(Ei\_MM)}{(\frac{A}{w}*y)} \quad [Pt * Kg * m^{-2} * years^{-1}] \quad (1)$$

$$Ui = \frac{(Ei\_U)}{(\frac{Q}{P}*h*Y)} \quad [Pt * W * m^{-3} * years^{-1}] \quad (2)$$

$$Ei = \frac{(Ei\_EoL)}{(w*y)} \quad [Pt * Kg^{-1} * years^{-1}] \quad (3)$$

The following parameters were used within the equations:

- Ei_MM: environmental impact of material and manufacturing phase (e.g., midpoint indicators GWP or HTP or endpoints);
- Ei_U: environmental impact of use phase (e.g., midpoint indicators GWP or HTP or endpoints);
- Ei_EoL: environmental impact of EoL phase (e.g., midpoint indicators GWP or HTP or endpoints);
- A: total cooking surface area [m^2];
- w: product weight [Kg];
- y: duration of the product [years];
- Q: maximum air flow rate [m^3/h];
- P: maximum power [W];
- h: hours of use per year [h/year];
- Y: timeframe considered in the scope of the study [years].

Within the equations, the unit "Pt" is considered for the unit of measure of the environmental impacts in different phases, knowing that it can be interchanged with the relative unit of measure of the considered LCIA indicators (e.g., $kgCO_2$eq. for the GWP indicator, $kgSO_2$eq. for the Acidification Potential). Thus, the final unit of measurement depends on the environmental impact indicator analyzed.

Mi was defined considering the ratio between the cooking surface area needed to be covered (A) and hood weight (w). This ratio defines the ability of the designer to use less material to cover the same area. Assuming that the same surface area is needed to be covered, if the weight of the hood is higher, then this ratio is lower, increasing the index result. The addition of the product duration (y) to the denominator is necessary to consider if a specific design choice increases the lifespan of the hood. *Ui* was defined considering the ratio between the maximum air flow rate (Q) and the maximum power (P), which are typical design/performance parameters, multiplied by the overall number of hours in the life cycle (h*Y). Being other design parameters very specific to the effective product use (e.g., motor efficiency), this equation considers the increment of the Q parameter, usually related to the increment of the P parameter. Assuming that Q is the same between two products, but one has a higher P, then this ratio is lower, increasing the index result (higher energy consumption). In addition, to consider that indoor air changing can be obtained with a system with less Q using the hood for a longer time, the overall hours of use in the life cycle are included in the denominator. *Ei* was defined considering the product weight (w) since it indicates how the EoL is performed and can detect if closed-loop EoL strategies are adopted for the product.

4. Results analysis for the cooker hoods case study

To make use of the indices, a selection of the LCA works performed on the cooker hoods was carried out. This household appliance family was chosen based on available data allowing the calculation of the developed indices. Although several papers have been published on this product family, only two works [19][20] can be used for the indices assessment, due to the lack of data not available in the other studies.

4.1. Products description

The article from Castorani et al., [19] focused on three different hood systems: Model A: conventional extractor hood (with constant airflow rate depending of the power setting chosen by the user), Model B: smart extractor hood (which automatically adjusts the flowrate of the hood based on the air quality detected by various sensors), and Model C: smart filtrating hood (equipped with a filtrating system instead of an extractor one as in Model B). The second study conducted by Bevilacqua et al. [20] almost ten years earlier, compared two hoods with a different motor: Model D: single-phase electrical motor, and Model E: inverter-driven three-phase induction motor. These five systems have been subjected to LCA according to two different LCIA methods (ReCiPe vs. Eco-Indicator 99, respectively). The adoption of two LCIA methods does not allow for a fair comparison between the indices calculated for midpoint indicators. Indeed, even if there are common midpoints indicators (e.g., Climate Change or Ozone layer depletion) a difference in the unit of measure is observed (e.g., [kgCO2 eq.] vs. [DALY] respectively for the ReCiPe and Eco-Indicator 99). However, it is possible to apply the presented indices to the endpoints knowing that the switching from midpoints to endpoints is based on characterization and weighting factors that can lead to misleading results.

4.2. LCA characteristics

The first research on the three hoods considers the phases of (i) production and material usage, (ii) use, and (iii) product end of life [19]. ReCiPe Hierarchist method, evaluated on a 100 years' timeframe was used as LCIA method. Secondary data from ecoinvent database, version 3.1 was used, while SimaPro version 8.05 was adopted as software tool. The functional unit is "Maintain good air conditions during the preparation of a complete daily meal consumed by a two-member family in Italy for 10 years". To accurately determine the time of usage required for each of the three systems, laboratory tests were carried out (Model A=95 [min/meal], Model B=92 [min/meal], and Model C=103 [min/meal]), assuming a usage frequency of 1 [meal/day]. The second study was conducted using a cradle-to-grave approach, considering raw material extraction, manufacturing phase, transport, use phase and EoL [20]. Eco-indicator 99 with an egalitarian approach, evaluated on a 100 years' timeframe was used as LCIA method. Secondary data from ecoinvent database were used (no version specified) while Gabi was adopted as a software tool. The functional unit defined within the study is "Standard size, steel and glass cooker hood of medium-high category, both in terms of cost and of extraction efficiency, with a maximum air flow of 600 [m^3/h], a maximum fan efficiency of 17% and an electrical motor consumption of 160 [W]". In the scope of this study, the product use was assumed to be 2 [h/day] over a lifespan of 10 years.

4.3. Data used

Some data necessary for the indices assessment and not reported in the papers were obtained by contacting the authors. Thus, the hood models assessed by the studies were retrieved, as well as the design features. These papers provided the minimum data required for the normalization of the results following the procedure proposed, as presented in Table 1.

Table 1. Main data used for indices calculation (NA – Not available)

Parameter	Model A	Model B	Model C	Model D	Model E
Ei_MM Human health endpoint	0.61 [Pt]	0.95 [Pt]	0.95 [Pt]	2.00 [Pt]	2.00 [Pt]
Ei_MM Climate change midpoint	18.03 [$kgCO_2eq$]	24.48 [$kgCO_2eq$]	24.48 [$kgCO_2eq$]	0.30 [DALY]	0.35 [DALY]
Ei_U Human health endpoint	60.80 [Pt]	32.89 [Pt]	22.88 [Pt]	11.70 [Pt]	7.89 [Pt]
Ei_U Climate change midpoint	1785 [$kgCO_2eq$]	920 [$kgCO_2eq$]	587 [$kgCO_2eq$]	4.38 [DALY]	3.25 [DALY]
Ei_EoL Human health endpoint	NA	NA	NA	NA	NA
Ei_EoL Climate change midpoint	NA	NA	NA	NA	NA
A [m^2]	0.42	0.42	0.42	0.34	0.34
W approx. [kg]	22	22	22	22	22
Q [$m^3 * h^{-1}$]	1000	1000	1000	600	600
P [W]	317	317	317	160	160
h [h/year]	578	560	627	730	730
y [years]	10	10	10	10	10
Y [years]	10	10	10	10	10

4.4. Results and discussions

By using the data presented in section *4.3* and applying the equations 1 and 2 referred to the cooker hood family, it was possible to compare the results obtained from the two studies. Fig. 3 presents the index result for the *Mi*, while Fig. 4 presents the index result for the *Ui*.

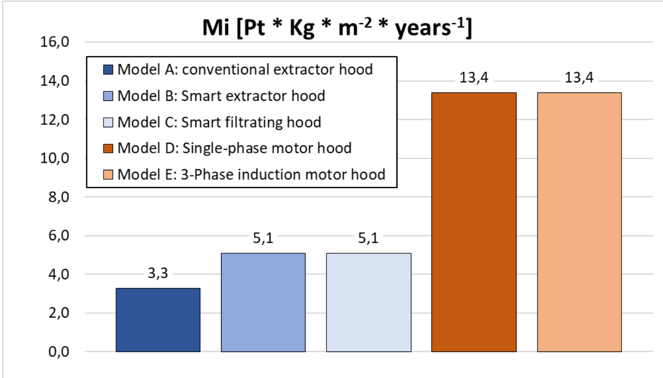

Fig. 3. Manufacturing Index (Mi) results (calculated for human health endpoint)

In relation to the *Mi,* it is worth noting that the conventional extractor hood (Model A) is presenting the best design option to limit the impact of its manufacturing when focusing on the Human Health endpoint indicator. The difference between the Model A and the two Models B and C for the *Mi* (Fig. 3) reflects a wider usage of electronic components (e.g., print circuit board) in smart devices. Indeed, Models B and C have more electronic components in the list of materials. Model D and Model E present a higher *Mi* compared with the other models, even if the overall weight is approx. the same. This outcome depend on two aspects: (i) the high environmental impact compared to the other hood models (2.00 [Pt] for models D and E, 0.95 [Pt] for model B & C, and 0.61 [Pt] for model A, respectively), and (ii) the different cooking surface area that are covered by the hood (0.34 [m^2] for models D and E, and 0.42 [m^2] for models A, B, and C). The difference in requirements and product features (i.e., the area covered by the hood) which would make impractical the comparison of the two products as presented in the original sources shows that the Model D and the Model E are worse designed than the other models. This finding comes from the ratio between the cooking surface area (A) and the product weight (w) which is in favor of the models A, B, and C (the same amount of material used to cover a bigger cooking surface area). Moreover, considering that the *Mi* has the environmental impact at the numerator and for the first three models (A, B, and C) the value is lower, the index indicates that materials and manufacturing processes are more sustainable for these three models. However, as previously mentioned, discrepancies in the *Mi* index could be also caused by the evolution of LCA databases (changes in the datasets) as well as by the different LCIA methods adopted in the two studies. For the use phase, once again the comparison of the two studies was not possible following the results of the two original sources since the products have different performances (Q and P) and assumptions (working hours). By using equation 2 for the *Ui* assessment, Model E seems to be the most efficient system, minimizing its impact related to the human health endpoint indicator, followed by Model D (both models are referring to the second research study).

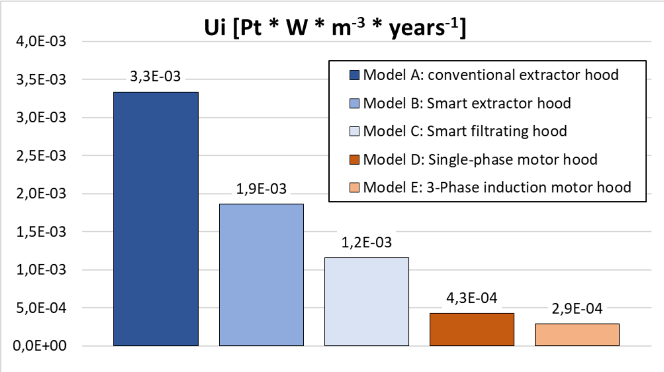

Fig. 4. Use phase Index (Ui) results (calculated for human health endpoint)

Based on these results, it emerged how the models analyzed in the work of Bevilacqua et al., [20] are the best in terms of environmental impact/efficiency ratio compared with the models analyzed by Castorani et al., [19]. This finding derives from the ratio between the maximum air flow rate (Q) and the maximum power (P) which is favor of the three models analyzed in the work of Bevilacqua et al., [20] even if the assumption done for the working hours is less conservative (respectively 730 [h/year] for models D and E, 578 [h/year] for model A, 560 [h/year] for model B, and 627 [h/year] for model C). Some minor differences in the results may be due to the use of different databases developed after 10 years, as well as the adoption of two different LCIA methods that are based on different characterization factors and weighting process.

5. Conclusion

In this study, new metrics for comparing the environmental impacts of household appliance design based on LCA studies are being developed. The novelty of these normalization metrics is the consideration of the performance of the systems, allowing a fair comparison among various assessments conducted according to different strategies. Although the approach presented here can be adopted for index definition of several families belonging to the large household appliances, only cooker hoods have been analyzed in this study. Other works dedicated to different systems are beyond this work. These studies will provide useful tips to conduct and compare LCA studies for other household appliances families, as well as to validate the approach for metrics definition and design parameters retrieval. The normalization procedure shall be applied with attention since the comparison of LCA results is allowed only when the same LCIA method has been used. Mathematical normalization for comparison between different LCIA methods would help in solving this challenge even if this research field is not related to the engineering design process but more to the LCIA method specialists. Finally, this paper paves the way for the next research, with the aim to apply the normalization method to other groups of electric and electronic equipment such as smartphones, laptops, etc. This research might be viewed as one of the first attempts in the LCA methodology progress to meet the requirements of each product sector. The aim is the creation of new standards relative to each product family, using the method and the outcomes to update or define new product category rules (PCR).

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